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## **Physical Model Study of a RCC Stepped Spillway for Renwick Dam, North Dakota**

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**Abstract.** *The North Dakota NRCS requested a specific model study of a RCC stepped spillway proposed for the rehabilitation of Tongue River Dam M-4, also known as Renwick Dam. The USDA-ARS Hydraulic Engineering Research Unit (HERU) constructed a two-dimensional, 1:8 scale physical model to evaluate the energy dissipation of a section of the structure. The proposed spillway entrance consists of a broad crested weir, with flow continuing down a 4(H):1(V) stepped chute. Prototype step heights ranging from 0.3 m (1 ft) to 0.61 m (2 ft) will be tested to compare the influence on energy dissipation. Stepped spillways provide a significant amount of energy dissipation compared to relatively smooth spillways. Additionally, stepped spillways require shorter stilling basins than smooth spillways, and the rough surface created by the step height influences the stilling basin design. The stepped spillway modeled with the larger step heights is expected to create more energy dissipation; thereby, creating the need for a shorter stilling basin and allowing for some cost savings. This research is expected to impact the development of design guidelines for stepped spillways planned on relatively flat slopes ( $\theta \leq 22^\circ$ ).*

**Keywords.** Stepped spillways, energy dissipation, stilling basins, rehabilitation, dams.

## Introduction

The Small Watershed Program administered through the USDA-Natural Resources Conservation Service (formerly the Soil Conservation Service) has provided technical and financial assistance for the construction of nearly 11,000 embankment dams across the U.S. These dams offer \$1.5 billion in benefits by providing flood protection, irrigation water, municipal and industrial water supplies, wildlife habitat and water quality improvement, and/or recreation. The peak of watershed dam construction for the NRCS was in the 1960's (Figure 1), and many of these structures were built to protect thousands of acres of farmland (USDA-NRCS, 2005). Since that time, land development around these structures has created a change in hazard classification, causing some of these structures to have inadequate spillway capacity. Hazard classification is the categorization of the failure potential of the dam as related to material damage and the potential loss of life caused by the failure. Additionally, many dams have completed the end of their planned service life. As a result, re-evaluation and/or rehabilitation of nearly half these dams will have to be addressed within the next 10 years.

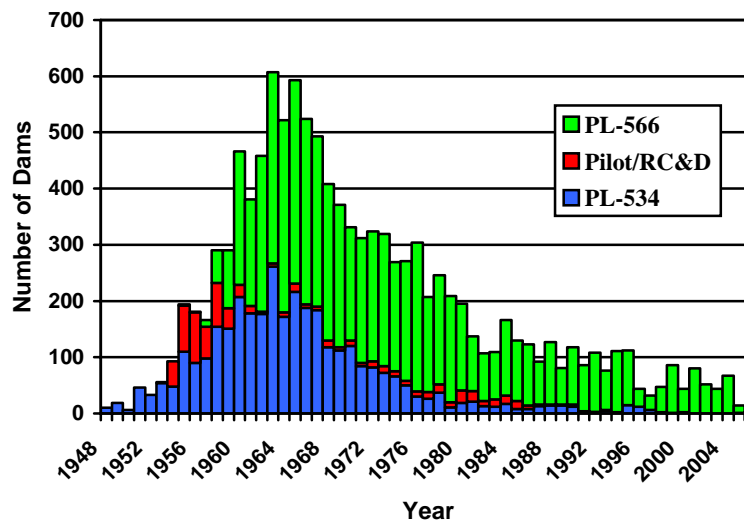


Figure 1. Watershed Dams Constructed by Year (USDA-NRCS, 2005).

Simply changing the dimensions of the existing embankment and/or associated spillways are not always viable options for rehabilitation because of land right constraints, topography changes, and urbanization. An economical alternative for structures faced with these challenges is roller compacted concrete (RCC) stepped spillways. RCC stepped spillways used in dam rehabilitation are typically placed over the existing embankment (Figure 2). As the spillway description indicates, the spillway stair steps down the downstream face of the dam. This stair step feature of the spillway creates a great amount of energy dissipation, allowing the use of a shorter energy dissipating stilling basin. RCC stepped spillways used on NRCS designed structures typically have flat slopes ( $\theta \leq 22^\circ$ ), and in some instances, they require convergence from the spillway crest to the downstream channel because of challenges created by urbanization or land right constraints. Design guidance for such structures are very limited, so often times, physical models are necessary to evaluate the hydraulic performance.



Figure 2. An example of an RCC stepped spillway.

## Stepped Spillway Modeling

The available design guidance on stepped spillways is limited, so some design engineers in both industry and government have expressed interest in stepped spillway research. Topics of interest include chute convergence, energy dissipation characteristics of relatively flat-sloped ( $\theta < 22^\circ$ ) versus relatively steep-sloped ( $\theta > 22^\circ$ ) chutes, and variable step heights. Flow convergence in stepped spillways causes significant run-up along vertical training walls and flow run-out along sloped stepped training walls (Hunt et. al, 2005, 2006a, and 2006b); thereby affecting the design of the spillway chute and energy dissipating stilling basin. The spillway slope and the step height affect the amount of energy dissipation in the spillway chute; thus influencing the design parameters of training walls and stilling basin as well. As a result, more information is needed to provide definitive design guidance on stepped spillways.

Models are scaled representations of a physical system that may be used to predict the prototype behavior of the system in some desired respect. Froude similarity is typically used to model hydraulic structures including stepped spillways because gravitational forces are typically the most dominant in these systems. To achieve Froude similarity, the U. S. Bureau of Reclamation (USBR) recommends that a Reynolds number greater than  $10^4$  be used in modeling hydraulic structures (USBR, 1980). Reynolds number describes the viscous forces, and if the appropriate Reynolds number is used, then viscous forces in most open channel applications are deemed negligible. However, highly air-entrained flow is expected in stepped spillways, and Boes (2000), Chanson (2002), Boes and Hager (2003a), and Takahashi, et al. (2005) among others have well-documented that scale effects are expected as a result. Scale effect is a term used to describe slight distortions that are introduced by the forces (i.e. gravity, viscosity, surface tension) involved in the modeled structure. Scale effects are typically apparent when the scale of the model is small. In highly air entrained flows, viscosity and surface tension cannot be ignored (Chanson, 2002 and Boes and Hager, 2003a). Chanson (2002) recommends that the scale of 10:1 or larger be used in modeling stepped spillways. Boes and Hager (2003a) recommend a Reynolds number of  $10^5$  and a Weber number of 100 to minimize scale effects in stepped spillway modeling. Weber number is a dimensionless number describing the ratio of inertia forces to surface tension forces. Takahashi, et al. (2006) recommends that Froude, Reynolds, and Morton similarity be satisfied for modeling highly air entrained flow, but Takahashi, et al. (2006) recognizes that this can only be achieved at full-scale. Morton number is a dimensionless term used to characterize bubble shape and can be calculated using a combination of Weber, Reynolds, and Froude numbers. A consensus among

researchers has yet to be agreed upon for the limits to minimize scale effects in physical models of stepped spillways.

Design engineers need to predict the energy dissipation in a stepped spillway so that the energy dissipating stilling basin may be properly designed. For this reason, scale effects should be minimized. Because the energy dissipation in a stepped chute is expected to be greater than what occurs in a smooth chute, the energy dissipating basin is expected to be smaller (Rice and Kadavy, 1996; Chanson, 1994, 2001, and 2002). Chanson (1994, 2001, and 2002) gives some guidance in determining the energy dissipation is steep ( $\theta > 50^\circ$ ), long stepped spillway chutes. The energy dissipation as proposed by Chanson (1994, 2001, and 2002) is

$$\frac{\Delta H}{H_{\max}} = 1 - \frac{\left(\frac{f_e}{8 \sin \theta}\right)^{\frac{1}{3}} \cos \theta \left(\frac{f_e}{8 \sin \theta}\right)^{\frac{2}{3}}}{\frac{3}{2} + \frac{H_{\text{dam}}}{d_c}} \quad (1)$$

where:  $\Delta H$  = total head loss =  $H_{\max}(H_{\text{res}})$

$H_{\max}$  = maximum head available =  $H_{\text{dam}} + 1.5d_c$

$H_{\text{res}}$  = residual head =  $d(\cos \theta) + \frac{q_w^2}{2gd^2}$

$f_e$  = friction factor of air-water flows

$\theta$  = chute slope

$H_{\text{dam}}$  = the dam crest head above the downstream toe

$d_c$  = critical depth at the spillway crest

For steep-sloped stepped spillways, Chanson (2002) estimates a friction factor of 0.2 for air-water flows. For flat-sloped stepped spillways ( $15^\circ < \theta < 22^\circ$ ), Chanson (2004) reports friction factors ranging from 0.1 to 0.28. Chanson also comments that the flow resistance and therefore friction factors for these flat slopes have been higher in prototypes than laboratory models. Chanson recommends using equation 1 to predict energy dissipation for slopes for which it was developed.

Boes and Hager (2003a and 2003b) developed a similar equation for predicting energy dissipation for a range of stepped spillway slopes by modifying equation 1 as proposed by Chanson (1994, 2001, and 2002). Boes and Hager proposed an equation to determine a normalized residual energy head in the gradually-varied skimming flow region for slopes ranging from  $19$  to  $50^\circ$ .

$$\frac{H_{\text{res}}}{H_{\max}} = \exp \left[ \left( -0.045 \left( \frac{s \cdot \cos \theta}{D_{h,w}} \right)^{0.1} (\sin \theta)^{-0.8} \right) \frac{H_{\text{dam}}}{d_c} \right] \quad \text{for } H_{\text{dam}}/d_c < 15 \text{ to } 20 \quad (2)$$

where  $s$  = step height

$D_{h,w}$  = hydraulic diameter =  $4R_{h,w}$

$R_{h,w}$  = hydraulic radius

This equation provides additional information when trying to determine energy dissipation in flat-sloped spillways and potential design requirements for the energy dissipating stilling basin. However, caution should be used with equation 2 outside the parameters for which it was developed when considering design requirements for stepped spillways.

In addition to Chanson, Peyras et al. (1992), Rice and Kadavy (1996), Yasuda and Ohtsu (1999), Chanson and Toombes (2002), Boes and Hager (2003a and 2003b), Gonzalez (2005), Hunt et al. (2005, 2006a, and 2006b), and Takahashi, et al. (2006) have researched flat-sloped ( $\theta \leq 22^\circ$ ) stepped spillways. These studies cover topics ranging from flow regime to energy dissipation to fundamental academic research on air bubble characteristics. However, additional information is needed to provide definitive design guidance on flat-sloped stepped spillways. Because design guidance for flat-sloped stepped spillways is limited, specifically for 4(H):1(V) spillway chutes, the North Dakota NRCS requested that the Hydraulic Engineering Research Unit (HERU) of the USDA-Agricultural Research Service conduct a model study of a stepped spillway having a 4(H):1(V) slope. The planned spillway is for Tongue River Dam M-4, also known as Renwick Dam. The proposed design and experimental research plan for this spillway are discussed herein.

## Rehabilitation Design Plans

Renwick dam is located six miles upstream of the city of Cavalier, North Dakota. The total drainage area for the dam is 380 km<sup>2</sup> (145 mi<sup>2</sup>). This structure provides flood control for downstream infrastructure including roads, bridges, farms, cropland, and the city of Cavalier. Today, it also serves as a recreation spot because of its location within Icelandic State Park. Construction of the dam was completed in 1961 as the lower structure in a series of nine other NRCS federally assisted constructed dams. Renwick Dam has been reclassified as a high hazard flood control dam because of the increase risk to loss of life and property.

Renwick Dam is planned for rehabilitation to comply with current state and federal dam design and safety criteria and to continue to provide flood protection. A RCC stepped spillway proposal was selected among eleven alternatives to bring Renwick Dam into compliance with the change in hazard classification because it met the economical, environmental, and/or social needs of the local residents/land users and project sponsors (Schmidt, 2006). RCC stepped spillways are often times selected for rehabilitation projects because

- They provide a substantial amount of energy dissipation, allowing for cost savings in the use of a shorter energy dissipating stilling basin.
- They can be placed over the existing embankment, saving additional costs in excavation and construction materials.
- They are more cost efficient to construct as compared to conventional concrete spillways because they have similar compressive strength as conventional concrete spillways without the need for reinforcing steel and because RCC can be placed with earth moving equipment (Portland Cement Association, 2002).

Decommissioning the structure, changing the dimensions of the existing earthen embankment and spillways, and removal of sediment from the sediment pool were among the options evaluated for this rehabilitation project. These alternatives and others were deemed unsuitable for this project because

- risk of flooding and loss of property and/or human life were too great
- the feasibility of the project made it impractical

- removal of sediment had little or no benefit towards flood storage and the reduction of the rehabilitation work (Schmidt, 2006).

Due to the lack of design guidelines for flat-sloped stepped spillways, specifically for stepped spillways having a 4(H):1(V) slope modeled with minimal scale effects, the North Dakota NRCS requested a model study from HERU to assist in the design of the structure. The North Dakota NRCS provided the following design elements for the proposed RCC stepped spillway:

- The RCC stepped spillway is to be placed over the existing embankment and is to pass the expected probable maximum flood (PMF) of  $1.45 \times 10^3 \text{ m}^3/\text{s}$  (51,300 cfs).
- The spillway will be approximately 150 m (500 ft) wide on a 4(H):1(V) slope (Figure 3).
- The spillway entrance condition will consist of a broad crested weir, and the proposed step height for the chute will be either 0.3 m (1 ft) or 0.6 m (2 ft).
- The spillway drop will be 11.6 m (38 ft).
- Because the amount of energy dissipation in the spillway chute is uncertain, the length of the stilling basin and the riprap size necessary to protect the downstream channel is unknown; however, the expected end sill height of 1.2 m (4 ft) has been set.

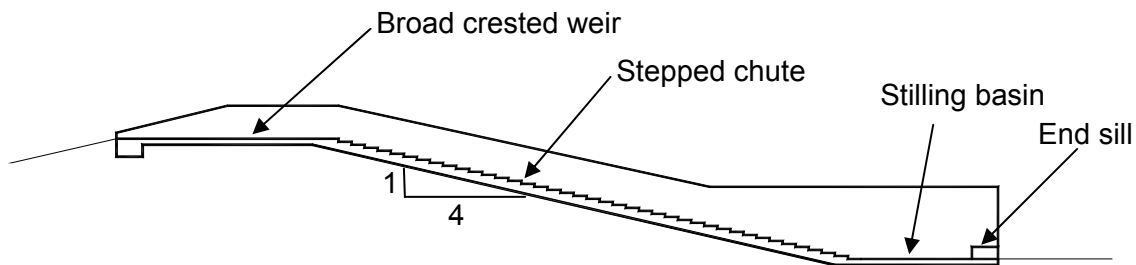


Figure 3. Renwick dam stepped spillway design plan schematic.

## Research Plans

The specific need of the North Dakota NRCS is design guidance related to the energy dissipating stilling basin and the riprap protection requirements for the downstream channel. To minimize scale effects, a 1:8 scale 2-D physical model of a 14.6 m (48 ft) wide prototype section of the proposed stepped spillway planned for Renwick Dam was constructed (Figure 4). Froude similitude was used to design the model. The Reynolds numbers for the model will range from a minimum of  $9.1 \times 10^4$  to a maximum of  $8.8 \times 10^5$ , and the Weber numbers are expected to range from 290 to 330, respectively. According to both Chanson (2002) and Boes and Hager (2003a), these parameters fit well within suggested guidelines to minimize scale effects. Model unit discharges ranging from  $0.1 \text{ m}^2/\text{s}$  (1.1 cfs/ft) to  $1.0 \text{ m}^2/\text{s}$  (10.6 cfs/ft) will be tested. These unit discharges represent prototype unit discharges ranging from  $2.3 \text{ m}^2/\text{s}$  (25 cfs/ft) to  $22 \text{ m}^2/\text{s}$  (240 cfs/ft). Multiple step heights including prototype 0.3 m (1 ft) and 0.6 m (2 ft) will be tested to evaluate differences in energy dissipation and air entrainment. Centerline water surfaces and velocities will be taken along the 4(H):1(V) slope and in the stilling basin. Water surface elevations beginning upstream of the spillway crest and concluding downstream of the stilling basin will be collected with a point gauge. Velocity measurements will be taken with a fiber optic air entrainment probe, a pitot tube, and/or an acoustic-doppler velocimeter depending on the air entrainment development within the chute. Velocity measurements are expected to be collected near the spillway crest; at stations 4.9, 9.8, 14.6, 19.5, 24.4, 29.3, 34.1, 39.0, 43.9,

and 48.8 m (16,32, 48, 64, 80, 96, 112,128, 144, and 160 ft), in the stilling basin, and downstream of the stilling basin. Velocity measurements will be used to determine the energy dissipation in the spillway chute. Energy dissipation and air entrainment on the spillway chute will be compared to previous research studies including the energy dissipation equation developed by Chanson (1994, 2001, and 2002) and the residual energy head equation developed by Boes and Hager (2003a and 2003b) . The stilling basin length is adjustable for determination of a proper size necessary to dissipate the energy before it is transported downstream. Riprap planned for the protection of the downstream channel will be evaluated. All experiments will be documented with a digital camera and with digital video. Construction of the model began in February 2007 with preliminary results expected by June 2007. This research is expected to impact the development of design guidelines for stepped spillways planned on relatively flat slopes ( $\theta \leq 22^\circ$ ).



Figure 4. Renwick dam stepped spillway model.

## Summary

The NRCS has provided federal assistance for the construction of nearly 11,000 flood control structures in the U.S. Many of these structures are faced with hazard classification changes due to the increased infrastructure surrounding them. Others have completed their planned service life and are in need of re-evaluation and possible rehabilitation. The rehabilitation options for many sites are limited due to land right constraints, topography changes, and/or location of infrastructure in the vicinity of the dam. One workable and economical solution for rehabilitation is placing a RCC stepped spillway over the existing dam.

Design guidance on RCC stepped spillways is limited, causing an increase in research in recent years. Design engineers have expressed interest in the application of stepped spillways on flat slopes ( $\theta \leq 22^\circ$ ) and stepped spillways requiring flow convergence. Additional information sought is the amount of energy dissipation that occurs on flat slopes and how energy dissipation on flat stepped spillways compares to predictive equations for energy dissipation on steeper stepped spillways. Guidance is also needed on the sizing of the energy dissipating stilling basin and riprap necessary to protect the downstream channel for flat stepped spillways. The North Dakota NRCS plans to design a RCC stepped spillway, and design engineers sought assistance from HERU for determining the energy dissipation on a 4(H):1(V) stepped spillway



and the effect the energy dissipation has on the required size of the energy dissipating stilling basin and riprap size necessary to protect the downstream channel. A 1:8 scale 2-D physical model such that scale effects should be minimal was constructed to evaluate the hydraulic performance of this stepped spillway. The results of the tests are expected by June 2007, and they are expected to impact the development of design guidelines for stepped spillways, resulting in cost-savings in future projects similar to the one herein.

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